ACKNOWLEDGMENTS

27. This paper results from a more general work on rotations published in the January issue of the *Journal of Navigation* and thanks are due to the (then) Director of the Royal Institute of Navigation, Michael Richey MBE, for his kind encouragement and generous support. Since the middle of last year, these ideas have been put to the Royal Meteorological Society with no success. However, the deep scepticism of Professor R. Pearce and of Dr Andrew Crane, kindly and patiently expressed, has done much to shape the pattern of this paper.

Manoeuvring Times, Domains and Arenas

B. A. Colley, R. G. Curtis and C. T. Stockel

1. INTRODUCTION. Two main concepts in mathematical modelling of ship encounters have been proposed by Davis.[1] The first, the 'domain', was an adaptation of a concept originally introduced by Goodwin,[2] who defined the domain as the 'area about own-ship that a navigator wished to keep free with respect to ships and other stationary objects'. The second, the 'arena', conceived by Davis, is the area around the domain which when infringed causes the mariner to consider whether to make a collision-avoidance manoeuvre. Thus, in a computer model, when a vessel enters the arena the computer analyses the situation and, depending on the severity of the threat, makes a collision-avoidance manoeuvre.

Goodwin's domain was divided into three sectors corresponding to the 'give-way', the 'stand-on' and the 'overtaking' regions as defined by the relative velocity of approach. The domain was derived from radar films of ship tracks and records of radar simulator experiments. Davis smoothed the sectored domain to a circle with own-ship off-centred astern and to port, and the weighting of each of the sectors retained. Davis's domain had a solid theoretical grounding; the arena, however, was simply a larger version of the smoothed domain. Its size and position were obtained by means of a well-distributed questionnaire. It served its purpose in the model, but lacked any real validation.

2. SPEED CHANGES. One problem with the Davis arena was its inability automatically to take into account different velocities, both of own-ship and of targets. Neither could it make allowances for continuously varying relative velocity. Finally it would not compensate for any loss of speed during a manoeuvre, which was a function to be built into the model at a later date. Holmes[3] has shown the importance of speed, both relative and absolute, to modelling of ship encounters. He constructed a mathematical model consisting of the independent variables *own-ship speed* and *target speed*, which predicted the dependent variable *indirect distance* (the distance from own-ship to target via the intersection of the courses). This gives some idea of the importance to be attached to speed changes in the model. In Davis's model different values of own-ship speed could be accounted for by using a speed-dependent scaling factor; this, however, became increasingly difficult, with changing values of target speed and relative velocity and it was decided to explore new concepts.

3. RANGE/RANGE RATE. Air traffic control theory[4] proved a useful source. The theory was to test the ratio of the range and range-rate (the closing relative velocity) against a time criterion. A manoeuvre was considered and if necessary executed when the time available became less than the time required for safe manoeuvre:

$$T_r > R/\dot{R} \tag{1}$$

where T_r is the time required (min.), R is the range to target (n.m.) $\dot{R}$ is the range rate (n.m./min.). This new concept uses the relative velocity of the vessels involved in the encounter and consequently compensates for any speed changes. Since the range/range-rate theory was first used in air traffic control it had to be capable of accounting for large speed changes, both relative and absolute, making it more than adequate for a ship-encounter model.

4. STAND-ON AND GIVE-WAY. It was decided to use a time criterion $T_r = 10$ minutes for give-way situations. This fits in well with the Davis arena for two vessels of 16 knots. An improvement of this time criterion will be attempted by means of a questionnaire. The next stage was to distinguish between give-way and stand-on situations. Rule 13 (*b*) of the Collision Regulations indicates that if a vessel is coming up with own-ship from a direction more than 22·5 degrees abaft the beam that vessel is overtaking, and own-ship should stand-on (Rule 10 (*b*)). In a crossing situation the vessel with the other on her own port-bow stands on (Rule 15). In a mathematical model this would be approximated by requiring own-ship to give way if the other ship approached from a direction between ahead and 22·5 degrees abaft the starboard beam, except that, if overtaking, the sector should be extended to cover the port bow. Initially it was felt that the Davis domain would serve adequately as a 'hard core arena' relating to the stand-on sector. It was, however, proposed that a model catering for speed changes in the give-way case should also do so in the stand-on case. This led to developing an equation for the safety distance for last-minute action (l.m.a.):

$$R_s = \frac{(U+V)}{60} * \frac{09}{\dot{\psi}} \tag{2}$$

where U is own-ship speed (knots) V is target-ship speed (knots) R_s is the safety distance for l.m.a. (n.m.) $\dot{\psi}$ is the rate of turn (degrees/min.). This fits in well with the present range/range-rate concept. If $(U+V)/60$ replaces $\dot{R}$ and $90/\dot{\psi}$ is regarded as the time required, then we have a new model for the stand-on case. The model can be further improved by modifying the time required to take account[6] of the ship's response time while setting the mariners' reaction time to zero as the target would already have been tracked visually at this stage. Thus in stand-on situations:

$$T_r = \frac{(90+A)}{\dot{\psi}} + T_d \tag{3}$$

where T_r is the time required, A is the derivation angle, T_d is the physical time delay before the vessel responds to the helm.

5. INITIAL PROBLEMS. The first problem with this model arose as the relative velocity tended towards zero when the two vessels were on nearly parallel courses, own-ship being overtaken. If the two ship speeds were nearly the same, therefore, the range at which the manoeuvre was considered, and if necessary executed, became very small. The polar diagrams, which assume a

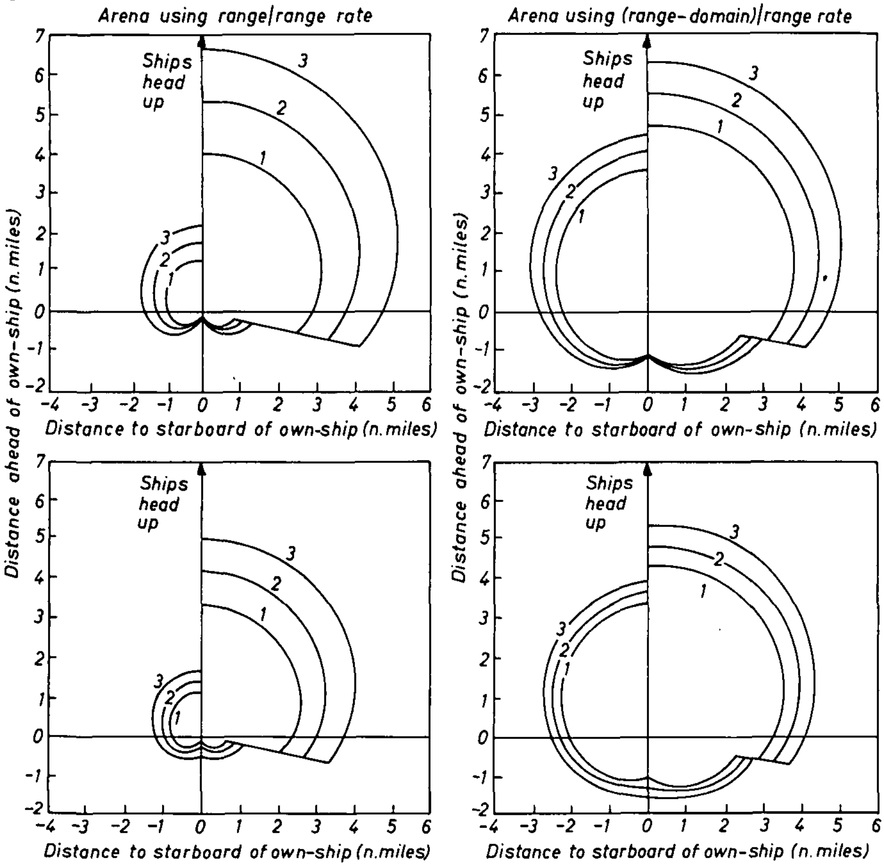

Fig. 1 Fig. 2

Fig. 1. Speeds in knots: (1) own-ship = 12, target = 12; (2) own-ship = 16, target = 16; (3) own-ship = 20; target = 20

Fig. 2. Speeds in knots: (1) own-ship = 10, target = 10; (2) own-ship = 10, target = 15; (3) own-ship = 10, target = 20

give-way criterion of 10 min., give the resulting arenas for a selection of own-ship and target speeds. The stand-on criterion was calculated using, in Equation (3), a rate of turn of 40 degree/min., a derivation angle of 20° and a delay of 0·5 min. (Fig. 1).

The problem occurred when the two vessels were of similar speeds in an overtaking situation. Since we were not at the time considering own-ship overtaking, the problem mainly affected the stand-on criterion. It did, however, have a significant effect on the give-way model.

6. SOLUTION. Rather than assessing the time available as the time taken for the target to reach own-ship, the mariner tends to gauge it as the time taken to reach an area around own-ship which he wants to keep clear of other ships, that is the domain. Thus the new model replaced range/range-rate by range to domain/range rate (RDRR); mathematically this was achieved by replacing Equation (1) by

$$T_r > (R - R_d)/\dot{R} \tag{4}$$

where R_d is the domain.

In the worst possible case of two vessels with identical speeds slowly converging, the minimum manoeuvring distance will be equal to the domain. The same principle was adopted for the give-way model but, since the original time criterion of 10 min. was obtained to best fit Davis's arena, it must be scaled down to cater for the addition of the domain. Thus a new give-way criterion of 6 min. was used.

The new mathematical model was similar to the ATC automatic warning standard, but our domain varies with relative bearing. In the ATC model there were a series of risk levels which could be employed. Each risk level used the range to a particular constant distance from own-aircraft (a circular domain around the aircraft). For each level it also had a unique time criterion. In the RDRR model the range was also taken to the edge of the domain, the difference being that our domain varies with relative bearing. The result is a risk level that varies as a function of the relative bearing. Thus, assuming the values for the domain and parameters defining the stand-on criterion remains as previously defined, and setting a new value of $\delta T_r = 6$ min. for the give-way criterion, the new arena shown in Fig. 2 was calculated. This significantly improves the model, with a minimum approach 1·03 n.m., occurring when own-ship was being slowly overtaken from astern.

The last refinement considered was a variation of the manoeuvring range with closest point of approach (CPA). It was concluded however, that since when using a domain to determine the threat of the target, the target was either regarded as a threat or completely safe, allowance for CPA and inclusion of the domain could not usefully go together. Thus, since the arena uses the domain in its construction it has no intermediate degree of safety or threat, and to incorporate an idea using CPA would go against the present principles.

7. CONCLUSION. The main advantages of the range-to-domain/range-rate concept are that the model automatically makes allowances for: (1) differing own-ship and target speeds; (2) changing relative velocity; (3) changes in own-ship speed through an alteration of course.

Other subtle improvements were possible. First, a development of the model could be a stochastic variation of mariners' reaction times to the arena. It would be a simpler task to integrate this into the RDRR model than to the Davis model. Secondly, when own-ship is overtaking, the Davis arena would demand that own-ship manoeuvres at the same range as if the vessels were on reciprocal courses. Davis investigated whether own-ship was in an overtaking situation, and it if was he would adopt a different model. With the new model, however, this was taken care of by the RDRR criteria. Even in the case where the two vessels were closing slowly and own-ship was overtaking, the minimum distance that own-ship would manoeuvre would be at the domain.

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An Inquiry into Simulator Training

Lieut. G. M. Veenman, R.Nl.N.R and
Lieut. Cdr. W. Verhage, R.Nl.N.R

Since 1975 the Royal Netherlands Naval College has operated a bridge manoeuvring simulator for the training of naval officers and petty officers of the deck department. There is a strong relationship between training objectives and performance abilities of a simulator and the way the two match defines the cost effectiveness and the value of simulator training. The training objective being the result aimed at (for a professional watchkeeper) consists partially of a combination of training subjects (things to be learned at the simulator). During 1980 and 1981 R.Nl.N.C. conducted a survey on simulator training subjects by means of an inquiry amongst Royal Netherland's Navy and Merchant Navy officers, marine lecturers (all of Dutch origin) and members of the International Marine Simulator Forum (IMSF). The results form the subject of this note.

The inquiry consisted of a personal information record and a questionnaire. Participants were divided into three categories: Royal (Netherlands) Navy, Merchant Navy and IMSF-members and extensive personal information records were added because preliminary experiments indicated that sub-groups in any of the three categories might give different results. It also offered the opportunity to study any correlation between sub-groups of respective categories.

The actual questionnaire listed twelve training subjects, an apparently random choice. The respondents had to award a priority number between 1 and 6 to the items listed, in relation to 'the adequate functioning of a watchkeeping officer'. The items had to comply with the following conditions: (*a*) belong to the professional abilities of watchkeeping officers; (*b*) be generally accepted as liable to be trained on a present-day bridge simulator. The list does not pretend to be complete. The twelve items were derived from a research project originated by United States Coast Guard.

The distribution of the questionnaire for categories Merchant Navy and IMSF was anonymous, and no exact response percentage could be measured. The Royal Netherlands Navy officers received personal letters and scored a 75.5 per cent response. Extrapolation of this extremely high figure to the other categories seemed unrealistic. However, the ratio between the number of forms sent to and received back from shipping companies and nautical institutes showed a significant response.

In general most respondents completed their forms accurately. Less than 4 per cent were scrapped due to erroneous entries. Since simulator experience in oil shipping is relatively wide, we regret not being able to present any results of this sub-group.

All data concerned were processed on the computer system of the